

# Aerodynamic Design of Heavy Vehicles

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# Quarterly Report

**Reporting Period:** April 15, 2001 through July 15, 2002

**Project Title:** Aerodynamic Design of Heavy Vehicles

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## 1.0 Activities and Accomplishments

### 1.1 Working Group Meeting

#### LLNL in April 2002

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on April 3-4, 2002. Team members including representatives from Georgia Tech Research Institute (GTRI) and Argonne National Laboratory (ANL) reviewed FY02 plans and presented status reports. DOE representatives Sid Diamond and Jules Routbort were in attendance and provided an update on the budget situation. Industrial representative Skip Yeakel from Volvo attended and gave a presentation that provided the industrial perspective.

### 1.2 Working Group Conference Call

The DOE Aero Team and ANL collaborators participated in a conference call on May 9<sup>th</sup>. The participants presented summaries of their planned activities, deliverables for FY02, and an update on their progress. The meeting emphasis was to identify areas where collaborative efforts can be enhanced.

Several conference calls have also occurred between Team members from Caltech and LLNL to discuss turbulence-modeling issues.

### 1.3 Statements of Work and Milestones for FY03

Statements of work with milestones for FY03 were constructed by each organization, reviewed as a group, discussed over a conference call on July 17th, and submitted to DOE.

### 1.4 United Engineering Foundation Conference

In preparation for the United Engineering Foundation (UEF) Conference titled *The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains*, the program and schedule have been established. Featured speakers were identified, contacted, secured and the title of presentations defined. Leads for invited sessions have been identified, contacted, secured, and the speakers for those sessions identified, contacted, and the abstracts have been submitted. To attract participants, an improved and updated general announcement was constructed and distributed. During this period, one co-chair and administrator made a visit to the Asilomar and the Monterey Aquarium to review the conference plans and the reserved facilities.

As a result of this intense effort, we have had a fantastic response of 60+ abstracts. We are expecting 80 to 90 conference attendees. We are continuing our efforts to raise financial support for the conference. In addition to the support by DOE, we have secured support from International Trucking and Engine Corporation for an evening social and LLNL has provided funds to support travel for speakers. We are waiting for a response from Freightliner Trucks, National Science Foundation, and the Society of Automotive Engineers (SAE). We have also asked SAE to consider publishing the conference proceedings as an SAE publication and they are currently reviewing our request. UEF has offered 1 student scholarship for an applicant that is within 10 years from receiving a bachelor degree.

## **1.5 Collaborations with Industry**

Jim Ross of NASA Ames and Rose McCallen of LLNL are working with Matt Markstaller of Freightliner in constructing a proposal to DOE for an experimental and computational effort.

## **1.6 Technical Accomplishments**

Each organization has provided a brief summary of their recent activities for the third quarter of FY02, which are attached. Overall, progress has been good and we are well on our way to a successful year in achieving our goals and deliverables. In summary, the near-term deliverables are to provide industry with

Guidance on the use of computational tools and

Insight into the flow phenomena for the design of low-drag heavy vehicles.

The guidance on computational modeling will be accomplished through the analysis of existing data with comparison to our Reynolds averaged Navier-Stokes (RANS) and large-eddy simulations (LES) and a hybrid method called detached-eddy simulation (DES). An understanding of gap-flow, base drag, frontal flow, and the effect of drag reducing devices will be gained from experimental analysis as well as the validated computations.

## **2.0 Future Plans**

Experimental tests in the 12-ft pressure wind tunnel at NASA Ames are planned for October 2002. DOE has requested a visit and meeting be held at NASA during this time to observe the experimental setup and review the project status. A date for this visit has not yet been established due to excessive existing time commitments of Team members and our DOE representatives. A post-conference meeting is being considered. In the interim, the Team will continue to have conference call meetings to share ideas, provide peer review, and keep each other up-to-date on our progress.

Our planning efforts continue for the UEF Conference. The Team members have submitted abstracts and are continuing work on their experiments and computations for presentation of their results at the conference.

# **Lawrence Livermore National Laboratory**

## **Quarterly Report**

**July 15, 2002**

Activities for this quarter include an effort to simulate the flow structure in the wake region of the trailer and in the gap region between the tractor and the trailer for the GTS geometry. Two-dimensional simulations have been conducted on both flow structures using LLNL's ALE3D code. With the information obtained from these calculations, three-dimensional (3D) grids are constructed for the wake and the gap regions. Due to complexity of the required grid generation, two different grid generation tools have been utilized. The ALE3D code and NASA's Overflow code are both being used for the 3D simulations; ALE3D for large-eddy simulation and Overflow for Reynolds-averaged Navier-Stokes simulations. The wake results will be compared to the NASA 7x10 wind tunnel experiment and the gap results to the USC gap flow experiment. The NASA 7x10 wind tunnel simulation has been finalized with two different grid topologies. These results will provide the proper boundary conditions needed for the GTS in the tunnel flow simulations. Significant progress has been made in understanding and applying the NASA's Overflow code and the overset grid technology. In addition, we continue to implement advanced algorithms in LLNL's models to improve simulation speed and accuracy and to verify and validate these advanced simulation tools.

### **Flow Simulations**

Simulations of the wake of the trailer and the gap are in progress. Unsteady flow simulations are performed with ALE3D and steady simulations with Overflow.

Several simulations are being setup for analysis of unsteady three-dimensional flow in the wake of a truncated GTS model, with and without boattails ( $Re=2.0e6$ , based on trailer width). The grid generation, which are non-trivial, for these simulations has been completed.° Several dozen initial attempts have been made to run these simulations.° However, progress has been hampered by an unexpected high frequency noise in the solution.° Efforts are being made to remedy this problem through the modification of boundary conditions and the model geometry. Using CAD definition of the modified GTS provided by USC, a simulation has been setup to analyze the unsteady three-dimensional flow structure in the gap using ALE3D. Again, progress has been slow due to convergence issues with various solvers in ALE3D. To improve convergence, several preconditioners are being tested.

Two simulations are being setup to obtain steady solutions using Overflow for the wake of the truncated GTS and the gap of the modified GTS. Grids have been constructed to utilize the overset capability of Overflow. The size of the wake grid is about 3 million elements and gap grid is about 5 million elements. Both simulations are running on Pentium PCs with Linux. Figure 1 shows preliminary results using the Overflow code.°

### **Verification and Validation**

Further verification of ALE3D is in progress. The laminar benchmark cases for the incompressible flow model in ALE3D have been completed and summarized in a report.° The two benchmark cases are flow over a flat plate at a nominal Reynolds number of 1000 and flow about a two-dimensional circular cylinder at a diameter-based Reynolds number of 1000.° For the flat plate, the results are compared with the Blasius boundary layer solution.° For the circular cylinder, both the drag coefficient and Strouhal number compares favorably with results from other studies in the literature.

### **Publication**

An abstract for SNL RANS results has been submitted to the UEF conference. The SNL RANS simulations of GTS model in NASA 7x10 wind tunnel included two grids each at 0° and 10° yaw. These results will be published as an LLNL internal

document and also as a UEF conference paper. Plans are to publish additional conference papers if three-dimensional results are obtained quickly enough to be pulished in the UEF conference.

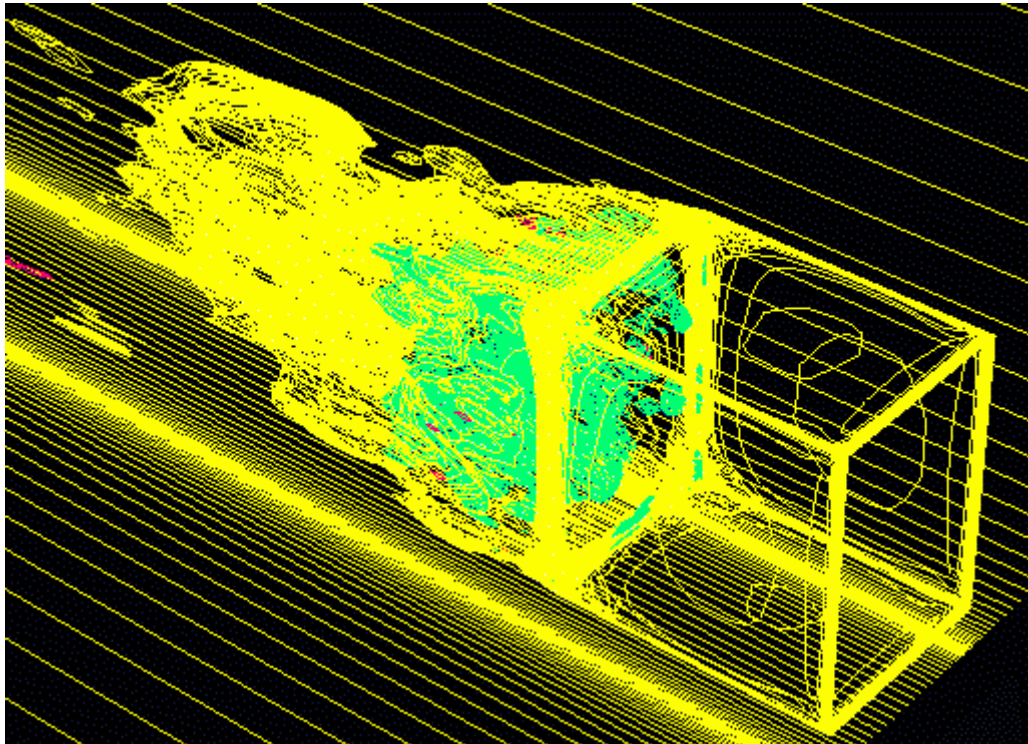


Figure 1. Contours of streamwise velocity at base of trailer showing flow separation at trailing edge and large base recirculation zone.

# **Sandia National Laboratories**

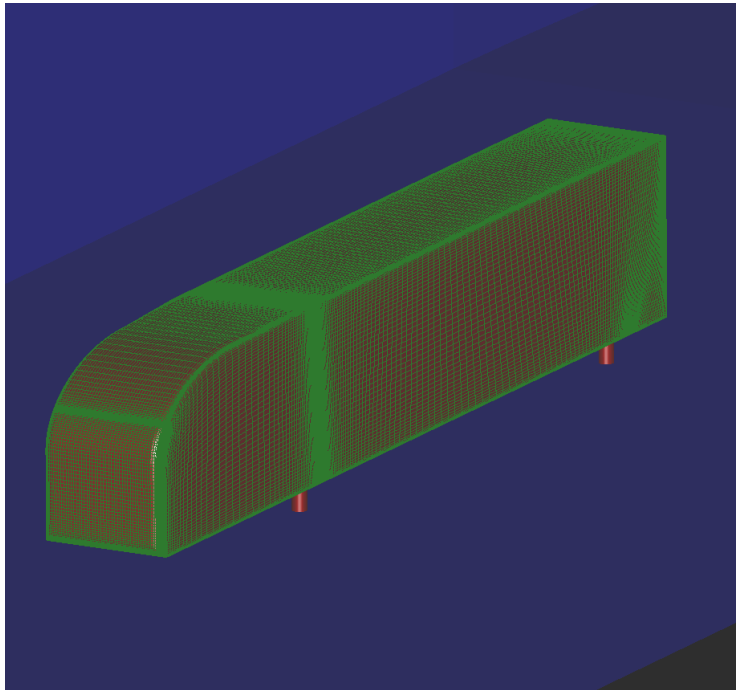
## **Quarterly Report**

**July 15, 2002**

SNL is responsible for evaluating the use of Reynolds Averaged Navier-Stokes (RANS) to predict the aerodynamic drag on a simplified model of a tractor-trailer vehicle. Over the past few years, Sandia's Navier-Stokes code, SACCARA, has been used to obtain RANS solutions using several different turbulence models. The results of these solutions indicated that the existing meshes did not have small enough spacing normal to the surface of the truck (i.e.,  $y^+$  in normalized turbulence coordinates). In FY02, one of Sandia's goals was to generate new 3D meshes and to complete the evaluation of the RANS method. A 2D mesh generation study was done to help define required mesh spacing for the 3D meshes.

The finest 3D mesh is complete and is shown in the figure below. Every other grid point was removed to obtain a coarser mesh which is referred to as the medium mesh. This process was repeated on the medium mesh to obtain a coarse mesh. The medium mesh contained about 2.5 million cells and was decomposed, using Sandia's DECOMP code, into 177 zones. The solution is set up to run on 165 processors on the teraflop computer. Some zones were combined on a single processor in order to balance the loading of the processors. A solution using the Spalart Allmaras turbulence model is currently running but not fully converged yet.

An additional goal in FY02 was to repeat the 2D grid studies using the new 3D mesh centerline spacing (previous 2D studies were based on old 3D meshes). These studies are not complete, but initial results indicate that the spacing on the centerline of the mesh is not producing expected  $y^+$  values. Based on these results, the 3D mesh will be modified to ensure the proper spacing. The process described in the paragraph above will be repeated when the new 3D mesh is available.



# California Institute of Technology

## Quarterly Report

July 15, 2002

Activities for the second quarter included development of a treatment for complex boundary geometries and development of a spectral computation algorithm (Fig. 1).

Because vortex particle methods for bounded, viscous flows require information at each of the irregularly-spaced field points about the closest point on the boundary, they have traditionally been limited to simple geometries such as the sphere or rectangular prism. During the second quarter we developed tools to extend the method to the more complex GTS, USC, and GSM geometries of interest to this group.

In particular, the closest point transform—which maps each field point to its closest boundary point—and also inside/outside determination, need to be computed rapidly. These require detailed information about how the boundary facets are connected, so the first project was to write code to assemble this information from a set of disconnected faces and orient them consistently. That project was completed, and we have been able to orient and compute connectivity for both GTS (Fig. 2) and USC geometries.

A number of closest point transform algorithms applicable to irregularly-spaced data exist in the literature. Our first attempt (Fig. 3) was loosely related to the LUB-tree method, but offered  $O(1)$  performance per test point. Unfortunately, the method required too much memory to be practical. A new method based on clipping against characteristic planes of the Eikonal equation is near completion. It will use far less memory, and should be fast, although the scaling has not yet been determined.

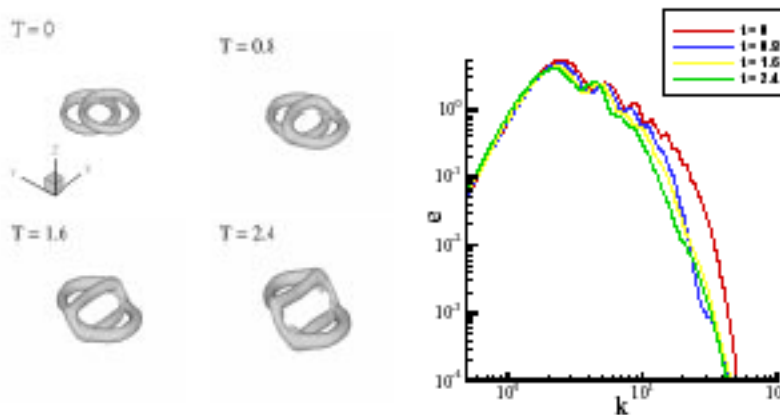


Figure 1: Stages in the collision of two vortex rings and the corresponding energy spectra



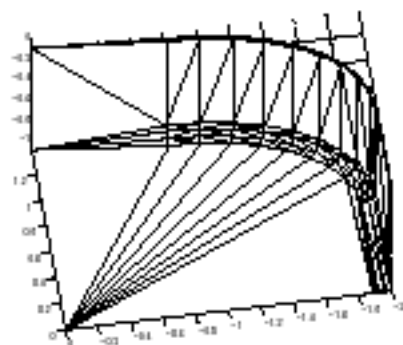


Figure 2: Simple connected triangulation of the GTS cab geometry

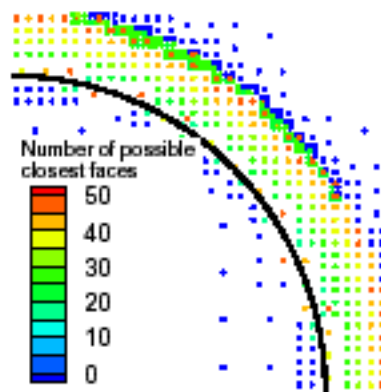


Figure 3: First closest-point transform algorithm applied to a sphere, diametral cut. Points mark the resulting cell centers.

# NASA Ames Research Center

## Quarterly Report

July 15, 2002

### The Measurement of Wake and Gap Flows of a 1/8<sup>th</sup>-scale Generic Truck using Three-component PIV

The Generic Conventional Model (GCM) is a one-eighth-scale truck model with high fidelity features in both the tractor and the trailer. This model was tested in the Army/NASA 7 x 10 Wind Tunnel at Ames Research Center. The model is simple enough for CFD gridding, therefore wind tunnel measurements of the wake and gap flows will provide the research community with data to validate CFD codes. Three horizontal planes in the wake and the gap were measured at two yaw angles at Mach 0.15. This corresponds to a Reynolds number of  $10^6$ . This paper will discuss the PIV system, samples of flow data and some of the observed flow features that contribute to aerodynamic drag.

The wake measurements taken were for two model configurations, a basic square-back trailer and a trailer with a drag-reducing fixture commonly referred to as plate boattail. The PIV plane was of a large enough area that the convergence of both the basic and the boattail configurations was rendered. Figure 1 shows the alteration of the wake by the boattail. Note the increased base pressure as expressed by higher velocity flow toward the back of the trailer.

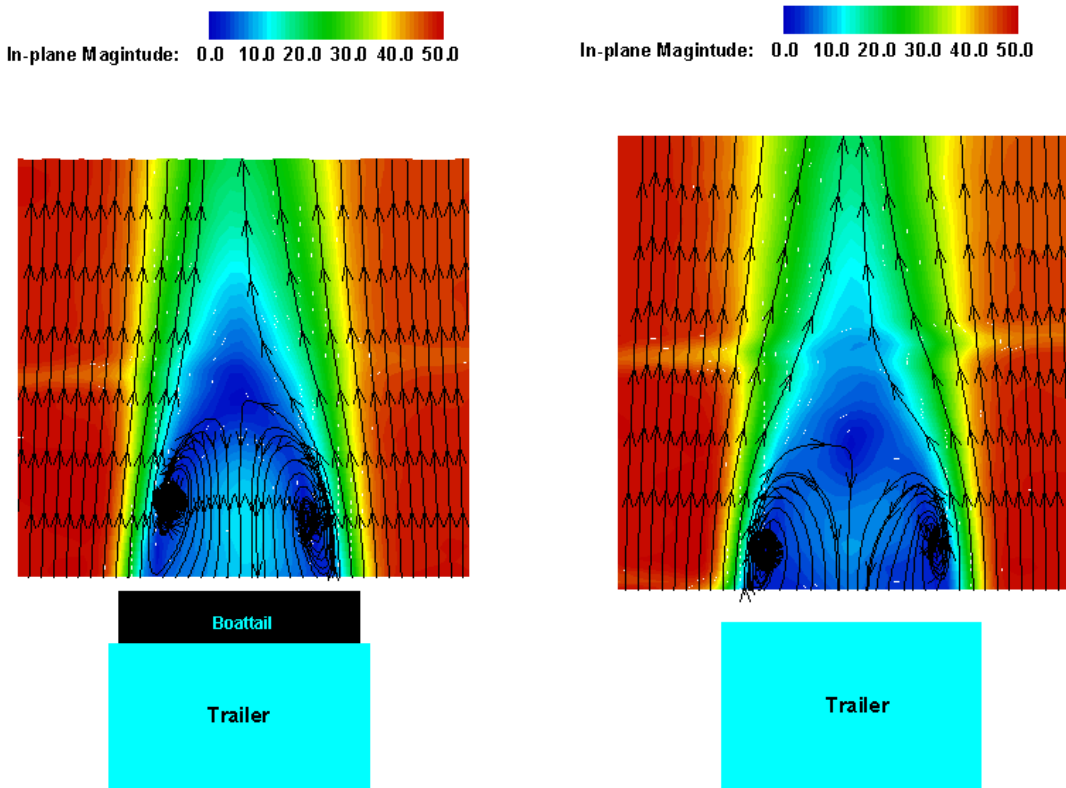


Figure 1. A comparison of the wakes of the boattail and basic configurations with the contour colors representing the in-plane magnitude of velocity.

The measurements in the gap were made on two model configurations as well. The basic configuration set the gap at the distance of 5 inches, which corresponds to the standard full-scale gap of 40 inches. The second configuration added 2.5inch (50% of gap) side extenders that were shown to reduced the aerodynamic drag. The side extenders were made of glass, thus permitting the observation of the flow by the PIV cameras. A strong hysteresis effect was observed on the aerodynamic forces and moments with the drag changing over 35% in the loop at yaw angles greater than  $10_1$ . The wind-averaged drag coefficients for the model without and with side extenders were 0.594 and 0.437, respectively. Besides reducing the drag, the side extenders also eliminated the aerodynamic hysteresis. Figure 2 is a plot of the axial drag coefficient vs. yaw angle. Note the high-drag state persists until a beta of 10+ degrees.

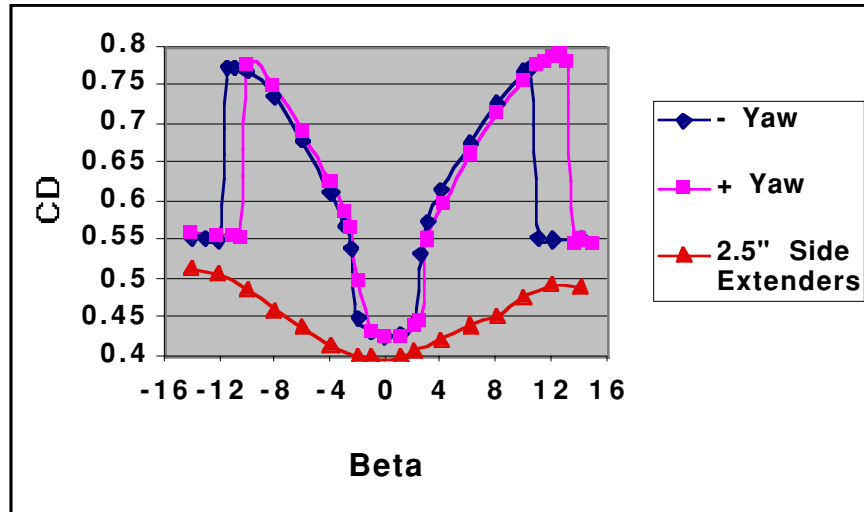
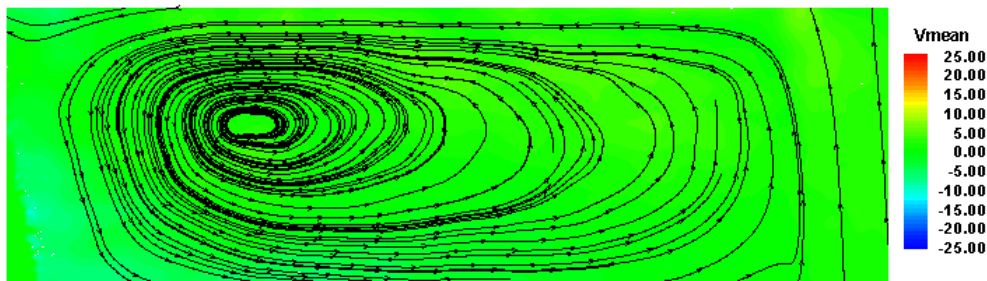


Figure 2. Plot of drag coefficient (CD) versus the yaw angle (Beta).

The flow feature that caused this hysteresis was observed in the PIV data. In Figure 3 the flow in the gap is plotted with stream tracers with the out-of-plane component of velocity in color contour. The view is from above with the free-stream approaching from below the plot. The plot covers 4.5 inches vertically and 14 inches horizontally. Note the lower velocity magnitudes and shift in the vortex structure in the low-drag state. The effect is considered to be Reynolds number dependent, this further investigations are needed to quantify the scalability of the wind tunnel data.

25% gap height, 11 deg Yaw, low-drag state



25 % gap height, 10 deg Yaw, high-drag state

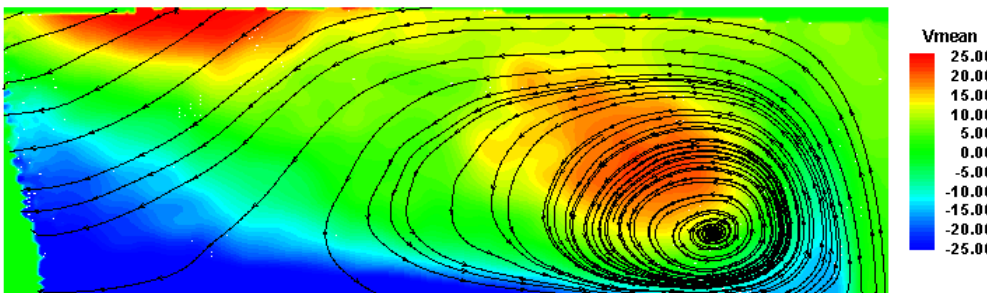


Figure 3. Comparison of the flow in the gap at 11 degrees showing the low-drag state with the flow in the gap at 10 degrees in the high-drag state. Contour colors represent the mean flow velocity across the gap.

# University of Southern California

## Quarterly Report

July 15, 2002

Summary of paper presented at the United States National Congress of Theoretical & Applied Mechanics, Blacksburg VA, June 24-28, 2002

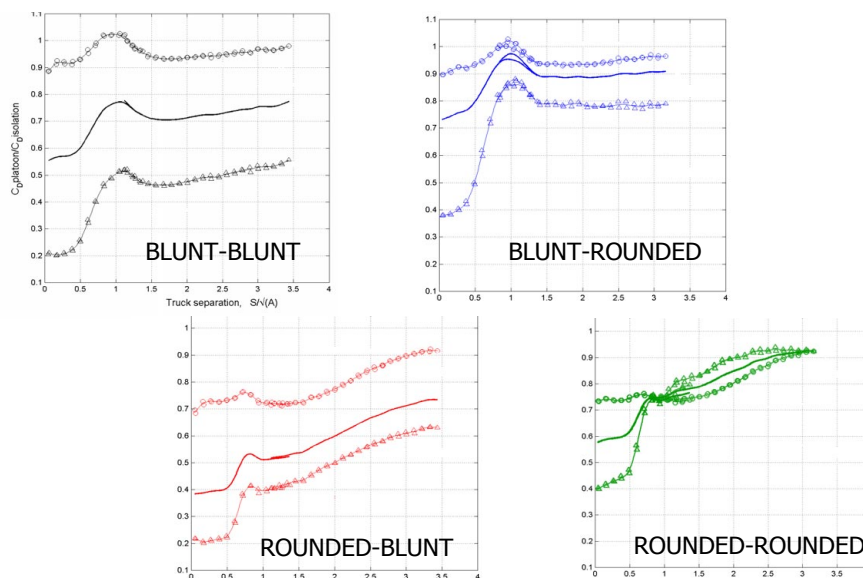
### *The Limits of Drag Behavior for Two Bluff-Bodies in Tandem*

Fred Browand & Mustapha Hammache, Aerospace & Mechanical Engineering, University of Southern California

The drags of two rectangular parallelepipeds are examined with bodies arranged in tandem and close enough together to strongly influence one another. Each of the two bodies can either be perfectly blunt at both ends (blunt) or can be fitted with an attachment that rounds the forward vertical edges (rounded). Simply rounding the vertical leading edges decreases the drag coefficient for the single body (body-in-isolation) from a drag coefficient of 0.92 to 0.46.

Four tandem configurations are tested, as in the figure below, which plots the value of the drag for either body as a function of spacing between the bodies in tandem relative to the drag of the same body in isolation. The body spacing is expressed as a multiple of  $\sqrt{A}$ , where  $A$  is the body cross-sectional area. These results show the remarkable drag savings to result from tandem operation. It is possible to understand the complex behaviors of the two bodies in tandem by considering, separately, the drag contributions arising from the fore-body and from the base of each body.

## Drag versus separation



The importance of the second and third panels is that these results bracket the possible savings obtained for more realistic truck models having wheels, cabs and trailers and drag coefficients in the range 0.5-0.65. The total savings for the two trucks taken together as a fleet-owner might operate the two trucks is shown in the figure below. The drag saving for the two model trucks, plotted as variously colored symbols, is never as great as the saving for the parallelepiped arrangement of minimum drag the red curve--nor is it ever so poor as the saving for the parallelepiped arrangement of greatest drag the blue line.

# Total drag summary

